Luminosity Determinations in Muon Colliders

IMCC and MuCol 2025

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Overview

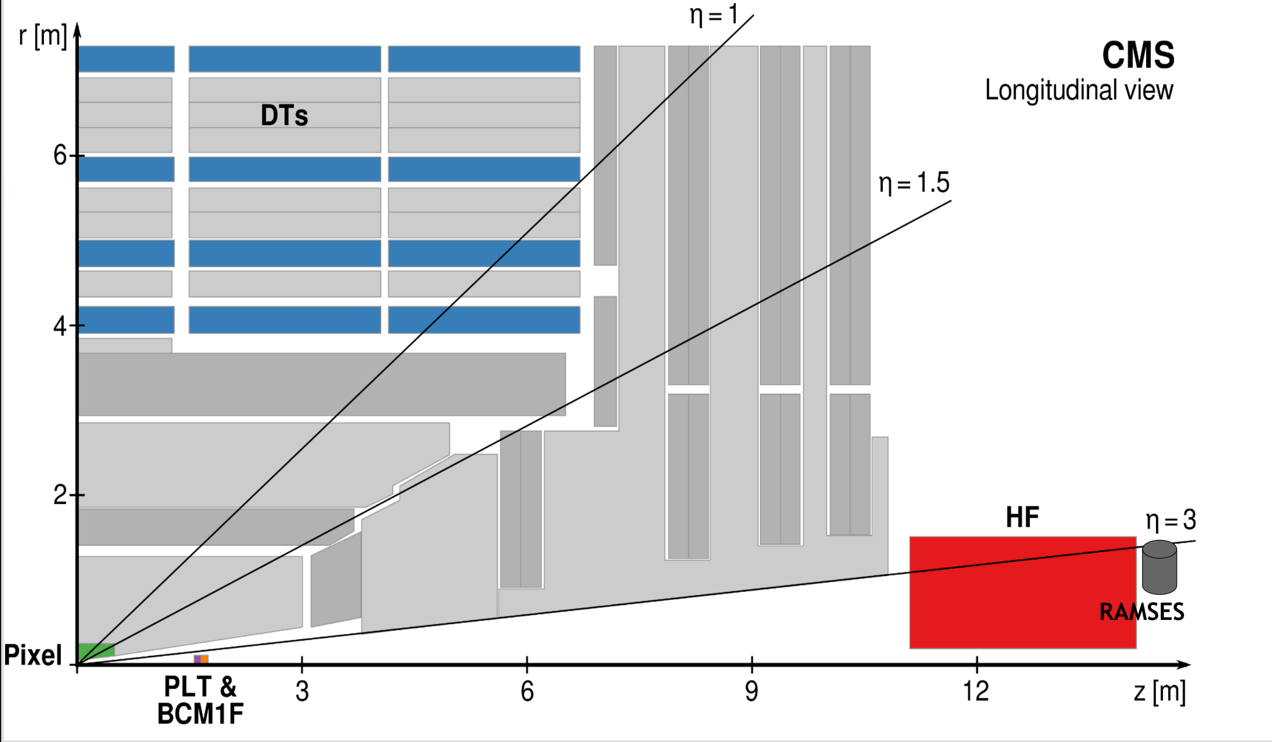
- Previous strategies and results at e^+e^- and hadron colliders.
- Luminosity measurement proposals for muon colliders.

LHC Proton-Proton Precision

- The precision in luminosity measurements at the LHC has tended to be in the 1-3% range, with a couple of sub-percent measurements.
- These measurements have two main areas of uncertainty:
  - Calibration (via van der Meer scans)
  - Luminometer stability
- CMS's current best measurement (2016, 1.2%)
  - Will go through a few details as an example.

CMS luminometers

- Primary luminometer: pixel detector using cluster counting (PCC)
- Secondary in 2016: Hadron forward calorimeter using towers above threshold counting: occupancy method (HFOC)

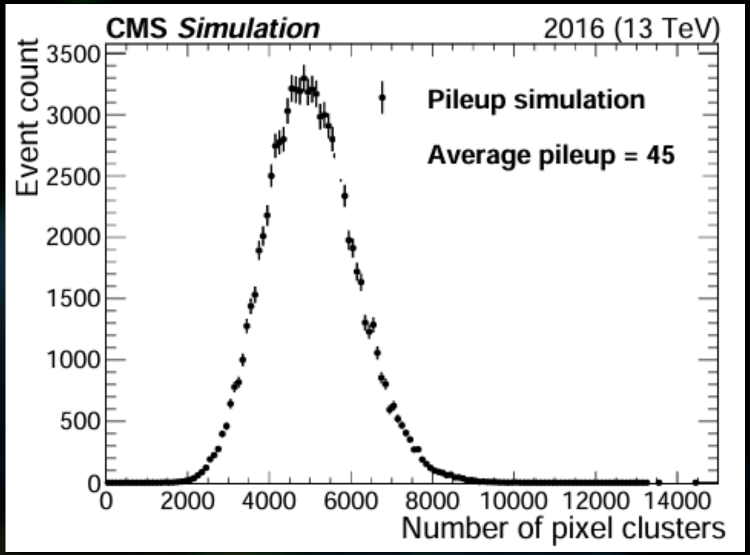


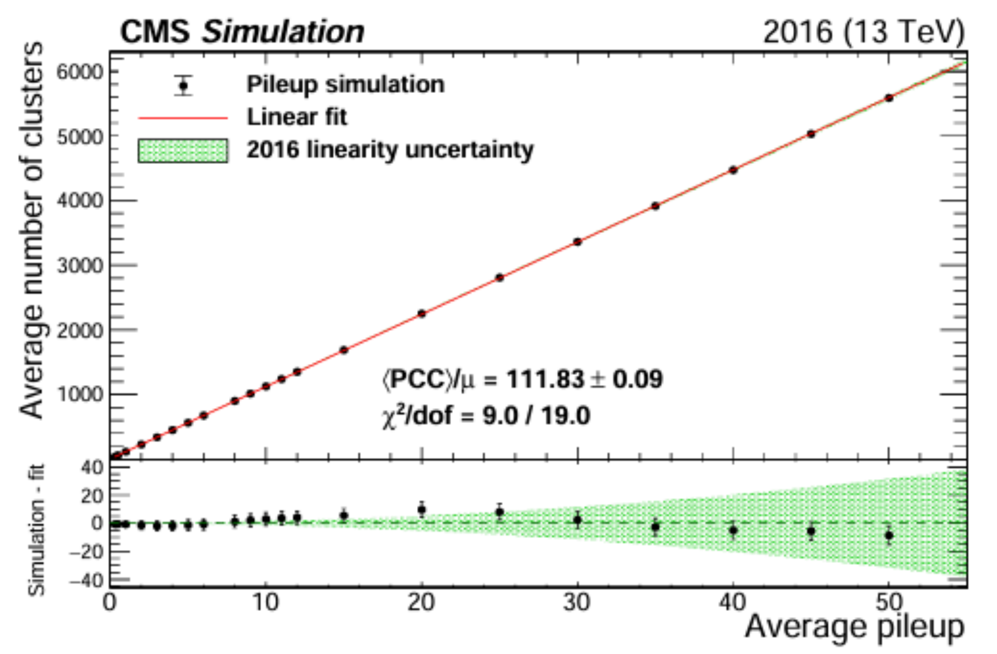
Rate-scaling: PCC, DT, RAMSES
Zero-counting: HFOC, PLT, BCM1F

arXiv:2104.01927
LUM-17-003

Pixel Cluster Counting

- The average number of charged particles is proportional to the number of proton-proton collisions.
- Since reconstruction is complex, the strategy in CMS is to count the clusters in silicon layers rather than number of reconstructed tracks.
- This method is very effective at low pileup as well, so if the number of tracks/clusters per collision is large enough, then it could work for online luminosity.
- For the moment this is an offline analysis in CMS, but there are HL-LHC luminometers (e.g., outer tracker and TPEX) with dedicated FPGA-based backends that will histogram counters per bunch crossing.





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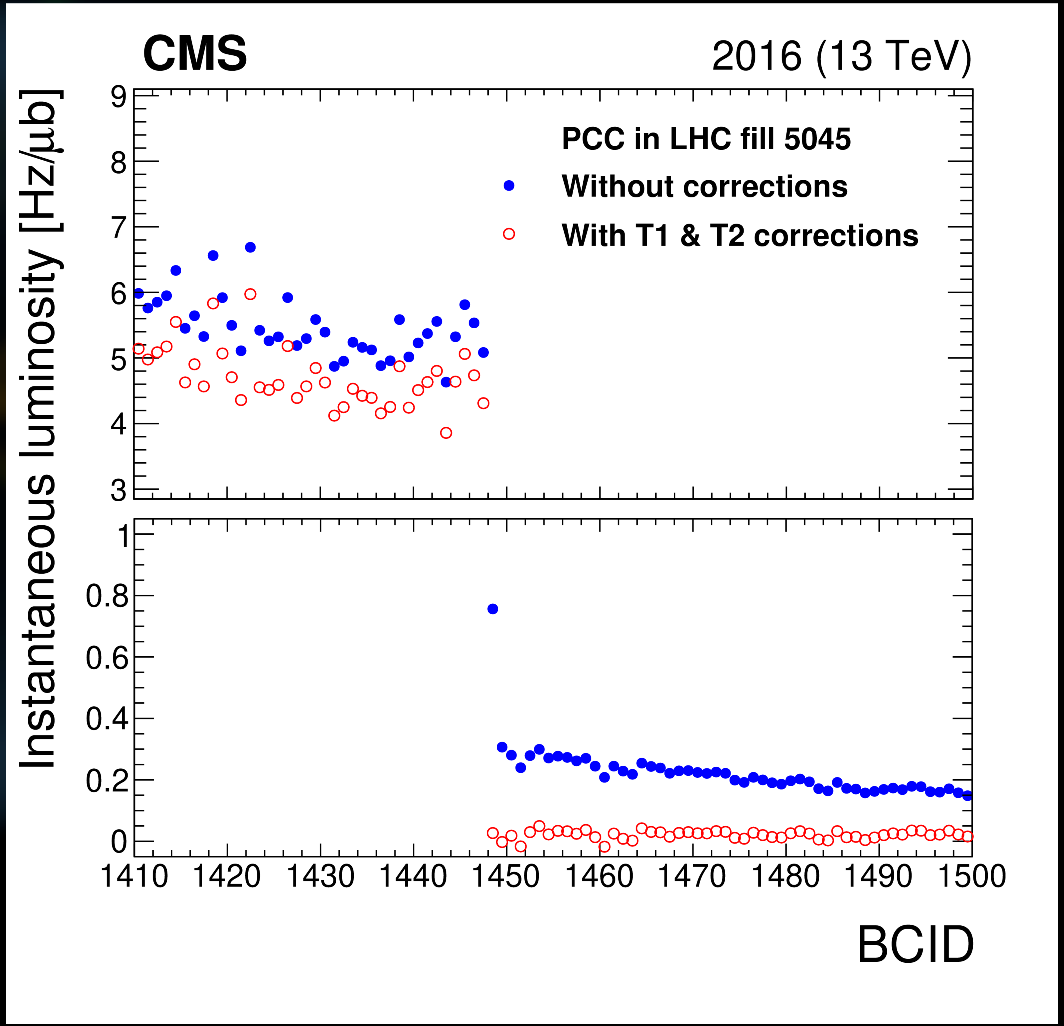
Pixel Cluster Counting

- There are a couple of ways to get clusters that aren't from collisions:
  - 1) tails of earlier, real clusters are visible (electronics spillover): just the next 1-3 bunch crossing slots
  - 2) detector material is activated and radioactive decays near the pixel detector creates new charged particles (afterglow): effect lasts on the order of the half-life of activated material.
- BIB can also be modeled and corrected in a similar way.



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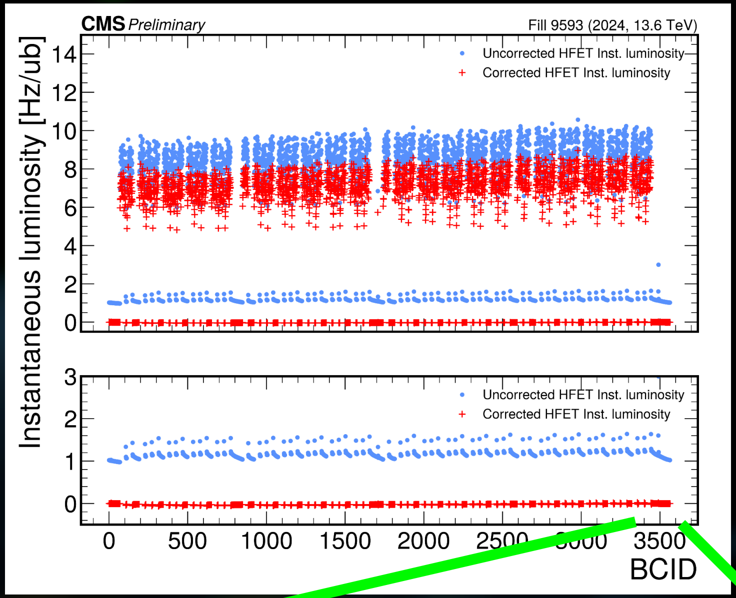
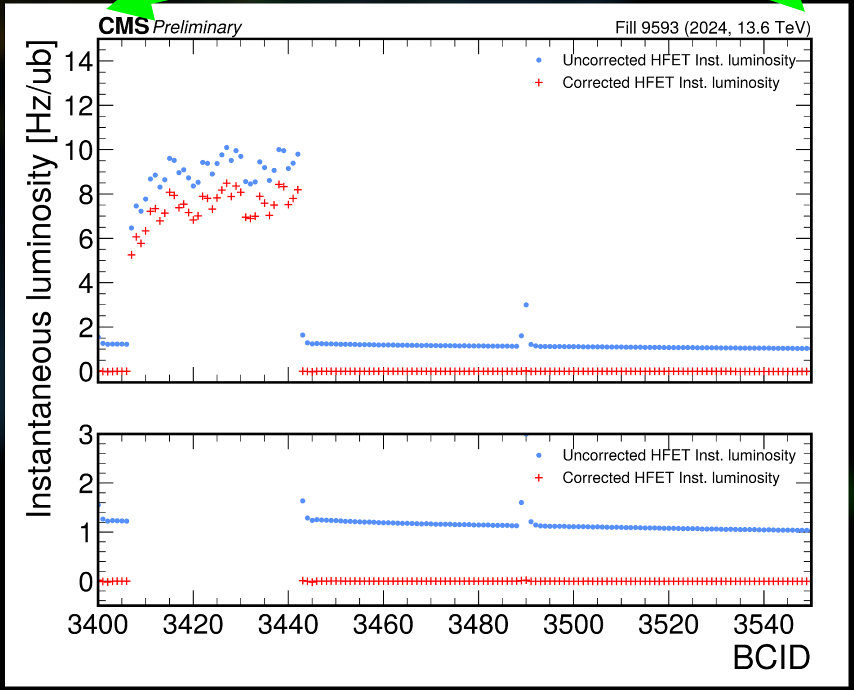
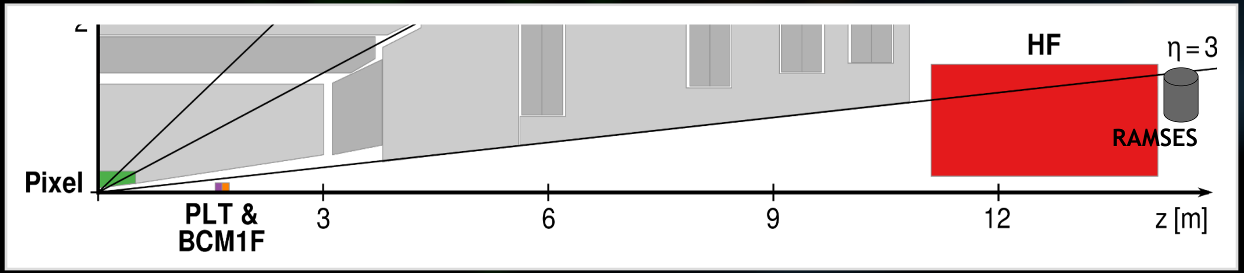
HF Lumi

- CMS's Hadronic Forward (HF) detector is an iron absorber with quartz fibers.
- An FPGA-based backend is used to store the histograms per bunch crossing.
  - They are readout every 1.45 seconds.
- The same strategy as in PCC is used for afterglow corrections.
- The corrections are much larger (~20%), but the size of the correction is different from the size of the uncertainty on the correction (<0.5%).
  - With a calorimeter-based luminosity measurement BIB could be handled with a similar approach.







Absolute calibration: σ_{vis} from vdM method

- Rate as a function of separation provides beam overlap widths in x and y
  - Visible cross-section assuming transverse factorization:

$$\sigma_{vis} = \frac{1}{\mathscr{L}_0} R_0 = \frac{2\pi \Sigma_x \Sigma_y R_0}{N_1 N_2 f_{LHC}}$$

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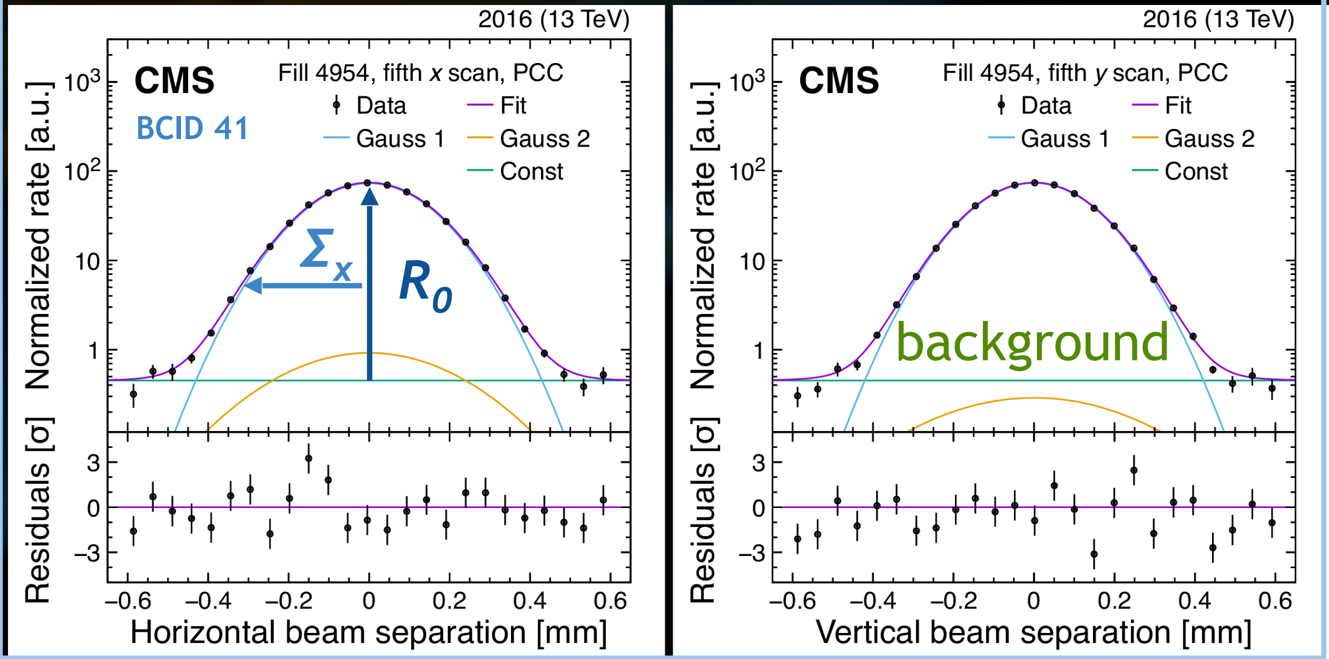
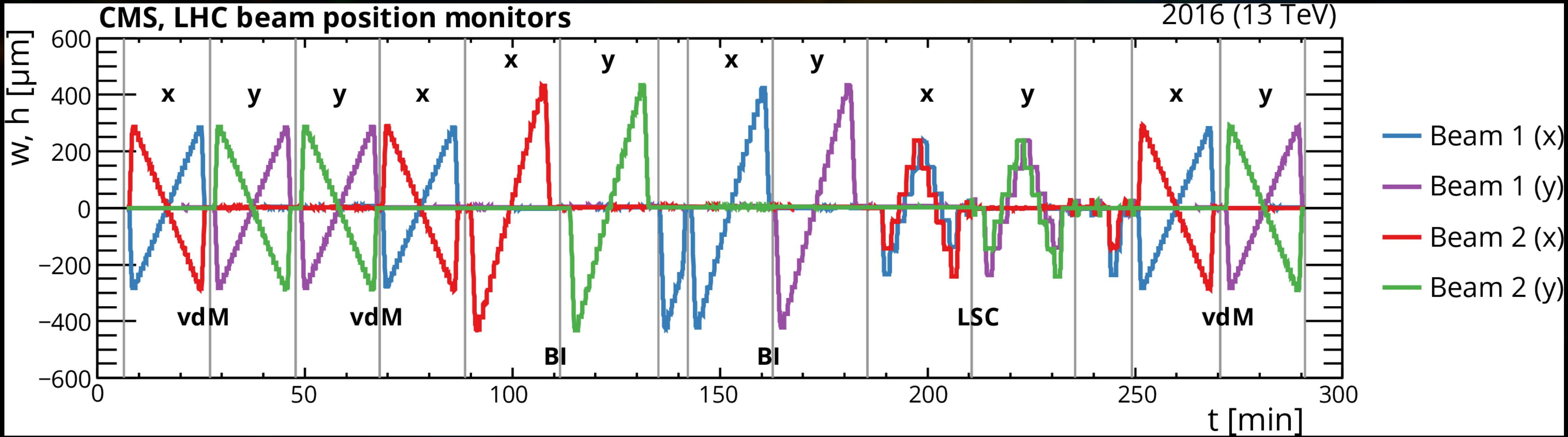
PCC: zero-bias data gated at 5 BCIDs at 20 kHz rate



- Effects to consider:
  - Bunch intensity (N1, N2)
  - Length-scale & orbit movements affecting separation (Σ_x, Σ_y)
  - Background affecting R_0
  - Beam-beam interactions

CMS 2016 vdM scan program

- Traditional **vdM scan**: beams move in 25 steps of 30 s each to scan separation range of ±6σ_{beam}
- **Beam-imaging scan** (BI): one beam fixed, other moves in 19 steps of 40 s each over ±4.5σ_{beam}
- Constant-separation **length-scale scan** (LSC): 2 beams separated by 1σ_{beam} move together in 1σ_{beam} steps from -2σ_{beam} to +2σ_{beam} average position and then with -1σ_{beam} separation back in total of 5+5 steps of 60 s each



Final 2016 Results

$$\int \mathscr{L}dt = \frac{1}{\sigma_{\text{vis}}}\int R dt$$

- The reanalysis of this data halted the precision (2.5%->1.2%).
  - Released in 2021.
  - A lengthy saga about beam-beam effects distorting the beams' shapes delayed the results about a year.
- Some of these approaches could be useful if an alternative to vdM calibration is used for arbitrary observables.
  - Cross calibration to a very precisely known process would work.
  - Several processes would effectively decrease the statistical luminosity.

Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.5	0.2	No
Integration uncertainty			
Out-of-time pileup corrections			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
Detector performance			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
Data acquisition			
CMS deadtime	0.5	$<$0.1	No
Total normalization uncertainty	1.2	1.0	—
Total integration uncertainty	1.0	0.7	—
Total uncertainty	1.6	1.2	—

1.0%

0.7%

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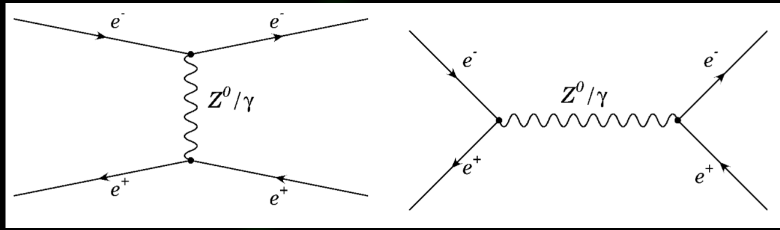
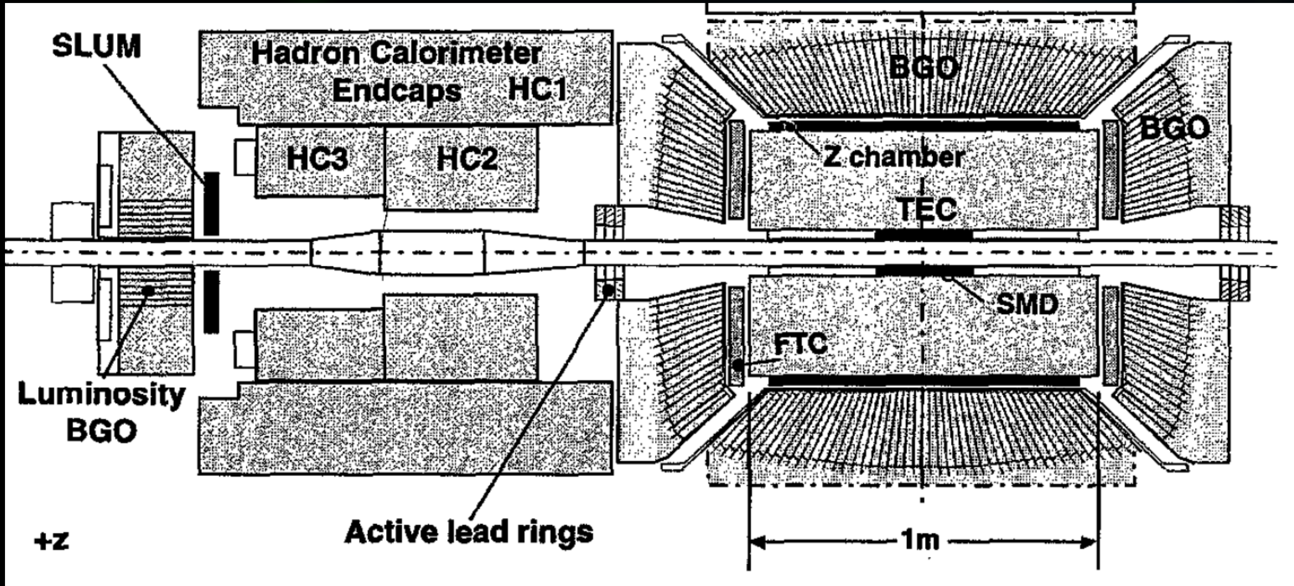
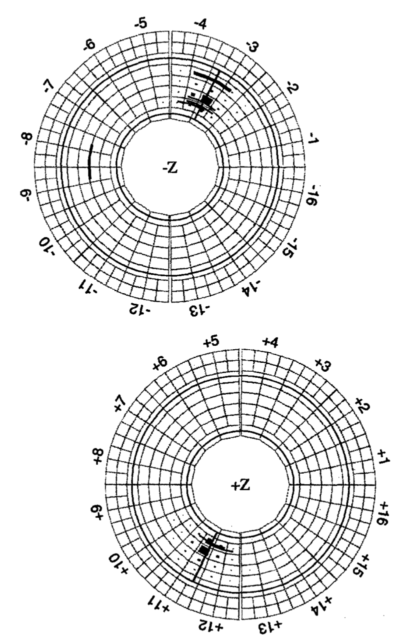
LEP Precision



- Small angle Bhabha scattering is a purely QED process, can be calculated with high precision.
- All of the LEP experiments were able to achieve less than per mille level (<0.1%) precision.
- E.g. L3 published 0.08% (0.05%) on 1993 (1994) datasets.





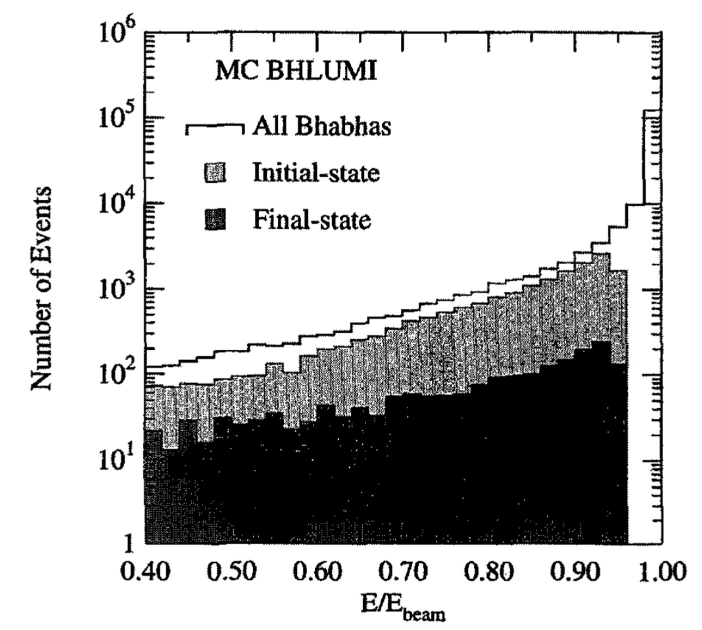


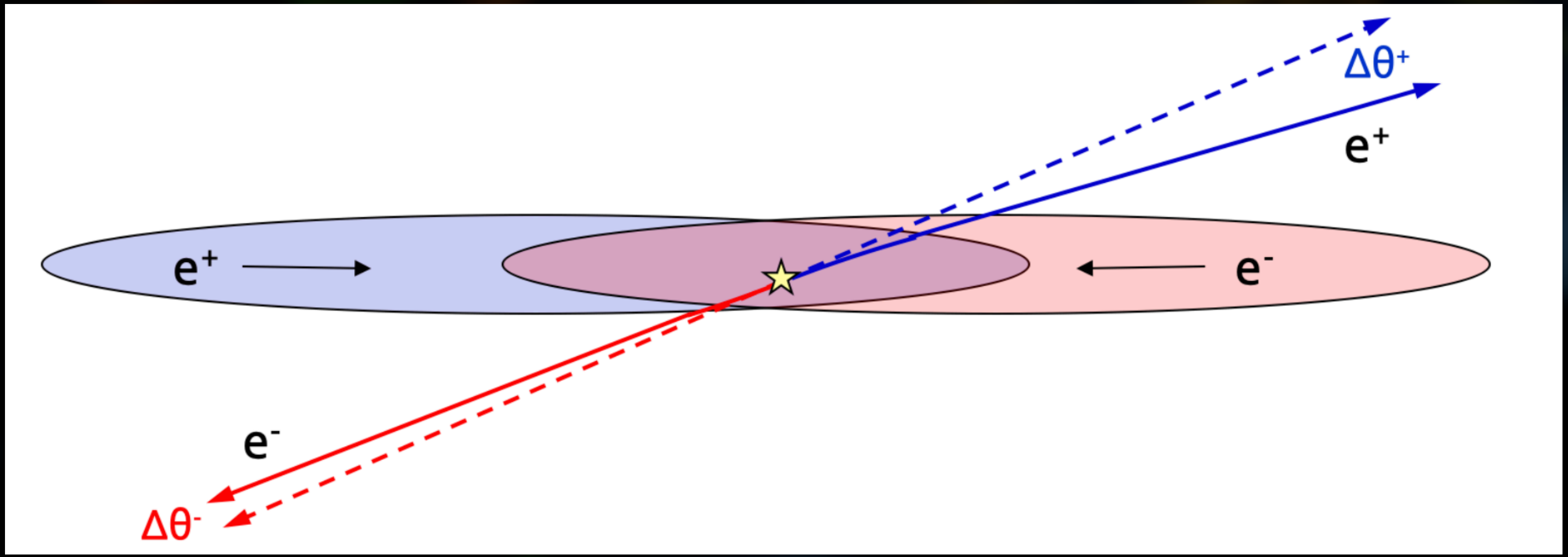
Fig. 39. $e^\pm$ energy distribution for all Monte Carlo Bhabha events. The initial-state radiation and final-state radiation events are indicated separately.

- Very forward! 32-54 mrad selection.
- One event
- Detailed analysis

 https://doi.org/10.1016/S0168-9002(96)00734-6

With Great Precision comes Great Responsibility

- Beam-beam effects can be very subtle. One published in 2020 resolved a 20-year 2σ tension in number of neutrino flavors.
- As the beams pass the outgoing electron/positron trajectories are altered by the magnetic field created by the beam.



$$N_\nu = 2.9840 \pm 0.0082$$

$$N_\nu = 2.9919 \pm 0.0081$$

https://doi.org/10.1016/j.physletb.2019.135068

Ideas for FCCee

- Bhabha has been the expected primary luminosity measurement up to now, but photon pair production from annihilation may be more precise.
- Both can potentially reach 10^{-4} in precision.

Luminosity Measurement Introduction

Two predominantly QED processes considered for e^+e^- collider abs. luminosity measurements at the 10^{-4} level (target especially for Z running for improving N_ν). Both can be under very good theoretical control.

1. **Bhabha Scattering**, $e^+e^- \to e^+e^-$. Used at LEP/SLC with small-angle Si/W-based calorimeters to restrict to the pure t-channel contribution. Current ILC and FCC-ee LumiCal designs follow this approach. $d\sigma/d\theta \sim 1/\theta^3$. Prone to systematics from knowledge of $\theta_{\min}$ and EMD bias.
2. **Pair Annihilation into Photons**, $e^+e^- \to \gamma\gamma$. A pure QED process. $d\sigma/d\theta \sim 1/\theta$. Less sensitive to $\theta_{\min}$ systematic. No $\theta_{\max}$. Lower event rate.

Integrated cross-sections are approximately:

$\sigma_{e^+e^-} = 1040 \text{ nb } (\theta_{\min}^{-2} - \theta_{\max}^{-2}) / s[\text{GeV}^2]$.

$\sigma_{\gamma\gamma}(\theta > \theta_{\min}) = 130 \text{ nb } (1 - P_{e^-}P_{e^+}) (\log_e(\frac{1+\cos\theta_{\min}}{1-\cos\theta_{\min}}) - \cos\theta_{\min}) / s[\text{GeV}^2]$

For $\theta_{\min} = 31.3$ mrad and $\theta_{\max} = 51.6$ mrad (OPAL LEP1), the cross-sections are **81 nb** (Bhabhas) and **115 pb** ($\gamma\gamma$ unpolarized) at $\sqrt{s} = 91.2$ GeV.

My Take

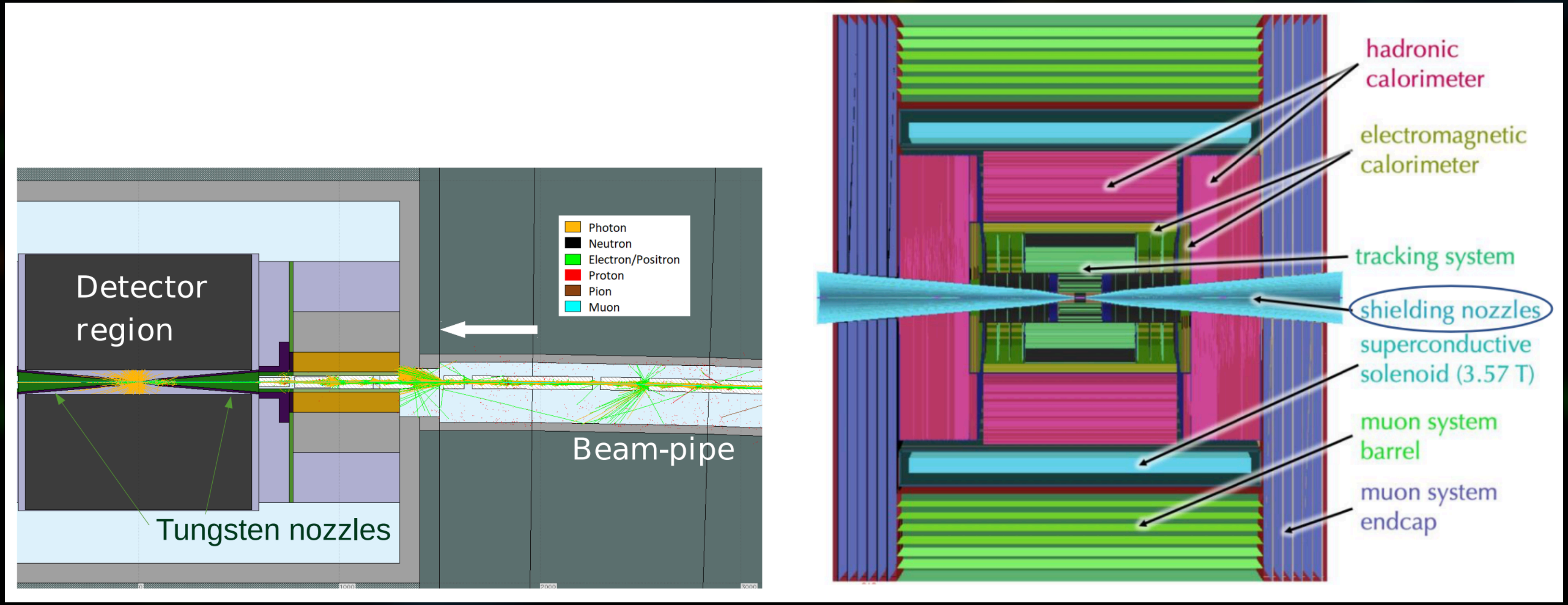
- Use Bhabhas for relative luminosity (especially for polarized beams).
- $e^+e^- \to \gamma\gamma$ can reach 10^{-4} statistical (at Z) with 1 ab^{-1} and $\theta_{\min} = 1.8°$.
- Precision **absolute** lumi. is experimentally easier with $\gamma\gamma$ cf Bhabhas.

Graham Wilson (Univ. of Kansas) | US e^+e^- Higgs Factory Workshop, FNAL+ANL | April 16, 2025 | 3 / 25

https://indico.fnal.gov/event/67484/contributions/312562/attachments/187210/258120/Fermilab-Apr2025_V2.pdf

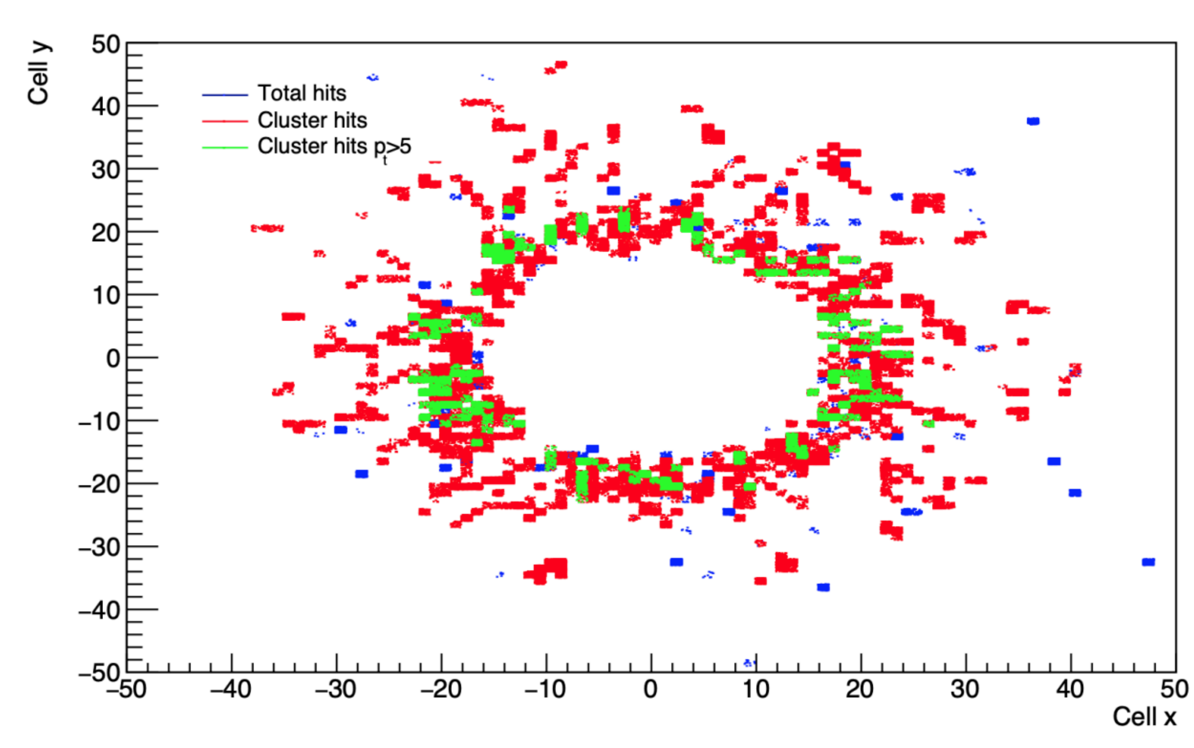
High angle μ-Bhabha

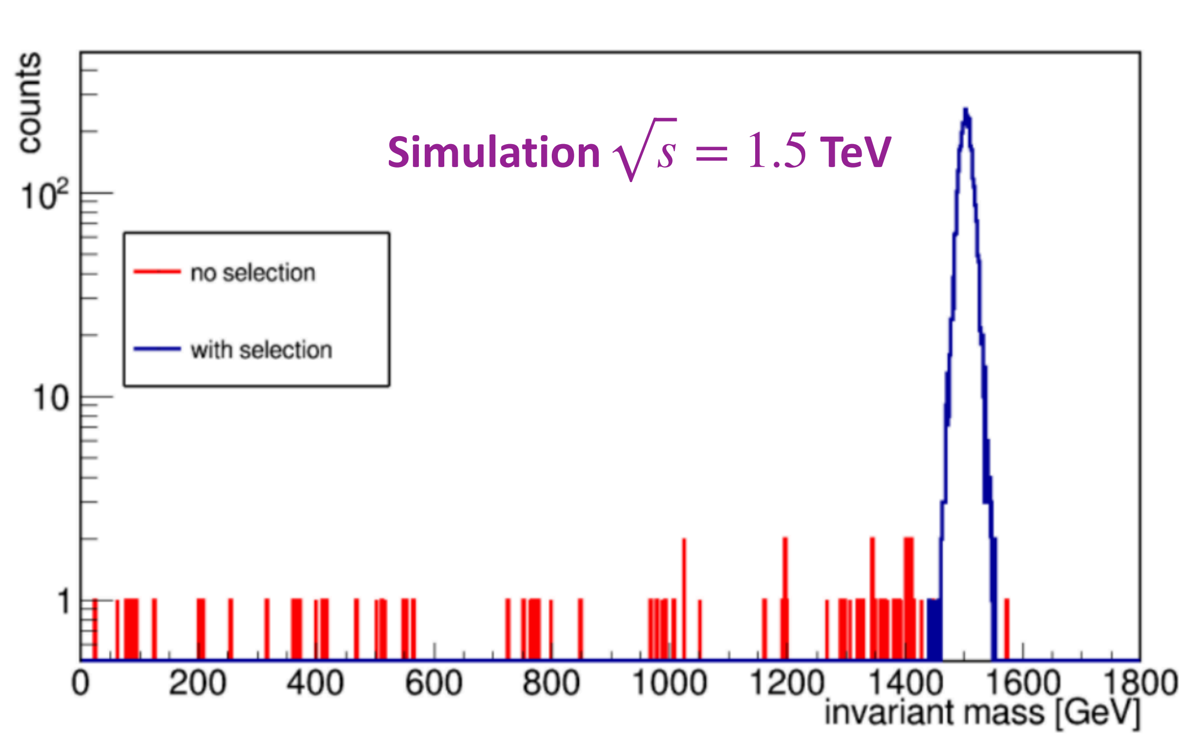
- High rates of beam-induced backgrounds require shielding nozzles near the interaction point.
- This reduces the angle available for LEP-like measurements.



High angle μ-Bhabha

- Fortunately, the cross section with $\theta > 15^\circ$ is large enough for sufficient number of events to remain for a measurement.
- From the Padua/INFN study, the statistic precision would be around 0.2% with year's data.





Conclusions

- Large angle μ-Bhabha luminosity uncertainties:
  - Uncertainty in θ_{min} in estimation in the theory cross section
  - Statistical uncertainty in smaller datasets
  - Other theory uncertainties? (NNLO precision is already at per mille.)
  - Uncertainty on beam-beam effects
- Potential alternatives and/or additional measurements
  - Di-photon final states (similar to μ-Bhabha, with lower cross section)
  - Track/pixel counting or calorimeter sums (a la LHC)